

# Decay of Resonances in Strong Magnetic Field

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**Abstract.** We suggest that decay properties (branching ratios) of hadronic resonances may become modified in strong external magnetic field. The behavior of  $K^{\pm*}$ ,  $K^{0*}$  vector mesons as well as  $\Lambda^*(1520)$  and  $\Xi^{0*}$  baryonic states is considered in static fields  $10^{13}$ - $10^{15}$  T. In particular,  $n = 0$  Landau level energy increase of charged particles in the external magnetic field, and the interaction of hadron magnetic moments with the field is taken into account. We suggest that enhanced yield of dileptons and photons from  $\rho^0(770)$  mesons may occur if strong decay channel  $\rho^0 \rightarrow \pi^+\pi^-$  is significantly suppressed. CP - violating  $\pi^+\pi^-$  decays of pseudoscalar  $\eta_c$  and  $\eta(547)$  mesons in the magnetic field are discussed, and superpositions of quarkonium states  $\eta_{c,b}$  and  $\chi_{c,b}(nP)$  with  $\Psi(nS)$ ,  $\Upsilon(nS)$  mesons in the external field are considered.

## 1. Introduction

Modification of  $\rho(770)$  decay properties in the magnetic field has been considered in relation to the possibility of  $\rho^\pm$  meson condensation [1] in sufficiently strong static magnetic fields. The paper [1] suggests that the lowest energy of charged decay products ( $\pi^+\pi^-$ ) is expected to exceed the mass of  $\rho^0$  meson at field strength  $eB \approx 0.14 \text{ GeV}^2$ . This means  $\rho^0 \rightarrow \pi^+\pi^-$  decays become suppressed and thus  $\rho^0$  meson can be "stabilized" in the magnetic field background [1].

One may immediately consider the possibility that strong decays of other hadrons can also be influenced in the magnetic field. Modification of decay probability into certain decay channels gives different branching ratios (BR) in the magnetic field when compared to the vacuum case. This may potentially affect reconstructed yields of resonances in heavy ion collisions, where very strong magnetic fields are expected to be formed for a very short time [2], and reconstructed yields of the observed hadronic resonance can thus become decay-channel-dependent.

In Sections 3, 4, 5 and 6 of this contribution we investigate to what extent  $\rho^0(770)$ ,  $K^*(892)$ ,  $\Lambda^*(1520)$  and  $\Xi^{0*}(1535)$  resonances may be affected by magnetic fields of strength  $10^{13}$ - $10^{15}$  T, which may be present in collisions of heavy nuclei [2] at RHIC and LHC.

Because decay  $\rho^0 \rightarrow \pi^+\pi^-$  is the only possible strong decay channel of  $\rho^0$  meson, the enhancement of dilepton and photon production from  $\rho^0$  decays can occur if  $\rho^0 \rightarrow \pi^+\pi^-$  decay is closed for whatever reason. In Section 4 we speculate that excess of photons and  $e^+e^-$  or  $\mu^+\mu^-$  pairs from  $\rho^0$  decays may be expected in the magnetic field of sufficient strength.

Decay properties of  $(q\bar{q})$  bound states in the magnetic field may be influenced also via different mechanism, which involves quantum superposition of  $J = 0$  singlet and  $L = 1$  states with  $J = 1$  ( $m_z = 0$  and  $m_z = \pm 1$ ) triplet states observed in Positronium [3, 4]. If such phenomenon happens in the case of hadrons [5], it may lead also to the enhancement of CP - violating decays  $\eta \rightarrow \pi^+\pi^-$  in the magnetic field. This interesting behavior is discussed in Sections 7 and 8.

## 2. Energy of charged particles in strong magnetic field

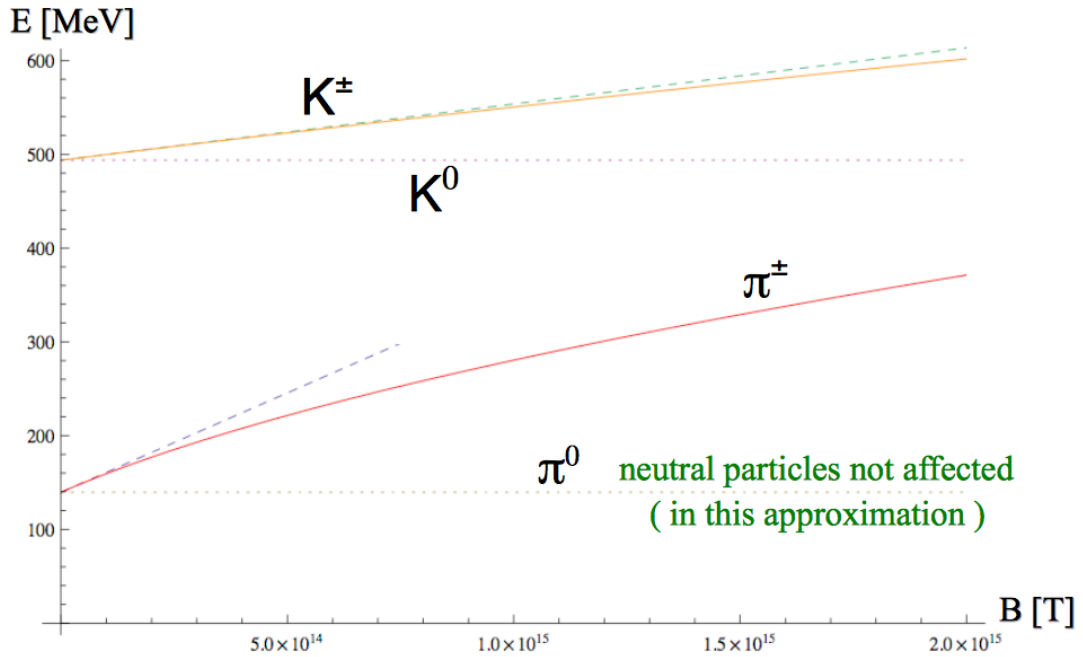
In the magnetic field, charged particle energy becomes quantized and for the lowest possible  $n = 0$  Landau level [6] the energy of electrons or positrons can be expressed as

$$E[B, s_z] = \sqrt{m^2 + p_z^2 + |Q|B - 2QB s_z} + \Delta E[B, s_z] \quad (1)$$

where  $m, Q$  are mass and charge of the particle,  $p_z$  is momentum parallel to  $\vec{B}$  field, and  $\Delta E$  is a correction for the anomalous part of magnetic moment (see below). For  $p_z^2 \ll m^2$ ,  $Q = -e$  and  $eB \ll m^2$  (assuming here  $\Delta E \approx 0$ ) one obtains ( $e$  is electron charge magnitude)

$$E[B, s_z] \simeq m + p_z^2/2m + eB/2m + eBs_z/m. \quad (2)$$

Term  $eBs_z/m$  on the right side of Eq.(2) corresponds to the energy of magnetic dipole in external field  $E = -\vec{\mu} \cdot \vec{B}$  with Dirac moment value  $\mu = s_z Q/m$ , and term  $eB/2m$  accounts for the lowest Landau level [6]. In Figure 1 we show how the energy of static ( $p_z = 0$ ) charged pions and kaons increases in magnetic field due to  $n = 0$  Landau level energy according to Eq.(1). Dashed lines are obtained using Equation (2) and dotted lines show the behavior of neutral ( $J = 0$ ) mesons.



**Figure 1.** Energy of  $\pi^\pm$  and  $K^\pm$  mesons (with  $p_z = 0$ ) in the magnetic field.

One can also read from Eq.(1) that energy of electrons with  $s_z = -1/2$  and positrons with  $s_z = +1/2$  does not change with magnetic field (if one neglects anomalous  $\approx 10^{-3}$  part of their magnetic moments).

Particles with internal structure have gyromagnetic ratio  $g$  substantially different from Dirac value ( $g = 2$ ) and "anomalous" magnetic moment needs to be taken into account properly. Energy dispersion relation for neutron in the magnetic field [7] is

$$E[B, s_z] = \left[ p_z^2 + \left( \sqrt{m_n^2 + p_T^2} - (2s_z)\kappa_n\mu_N B \right)^2 \right]^{1/2} \quad (3)$$

where  $\kappa_n = -1.91$  is neutron magnetic moment in units  $\mu_N = e\hbar/2m_p = 3.15 \cdot 10^{-14}$  MeV/T. For small magnetic fields:  $E[B, s_z] \approx m_n + (2s_z)|\kappa_n|\mu_N B$  is obtained from Eq.(3) using ( $p_z, p_T \approx 0$ ),

which corresponds to static magnetic dipole interaction  $E = -\vec{\mu}_n \cdot \vec{B}$ . We shall use Eq.(3) also for  $\Lambda$  and  $\Xi^0$  baryons with their magnetic moments  $\mu_{\Lambda^0} = -0.61\mu_N$  and  $\mu_{\Xi^0} = -1.25\mu_N$ . For neutral  $J = 3/2$  particles  $\Lambda^*(1520)$  and  $\Xi^{0*}(1530)$ , term  $(2s_z)$  in Eq.(3) can be replaced by  $(2s_z/3)$  for obtaining the energy of  $s_z = \pm 3/2$  substates.

Dispersion relation for protons in the magnetic field [7] can be expressed for  $n = 0$  Landau level as

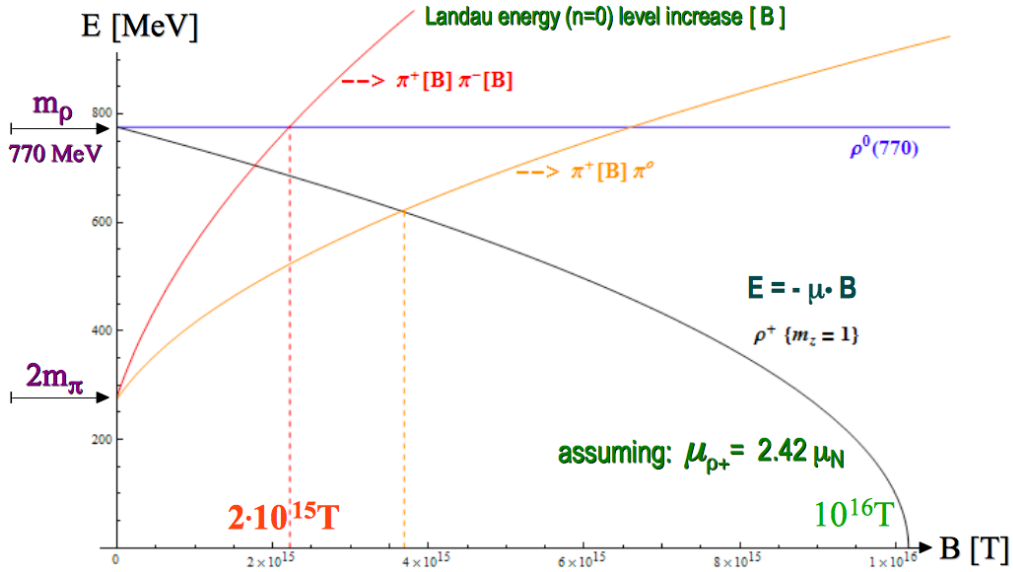
$$E[B, s_z] = \left[ p_z^2 + m_p^2 \left( \sqrt{1 + (1 - 2s_z)B/B_c^p - s_z \kappa_p B/B_c^p} \right)^2 \right]^{1/2} \quad (4)$$

where  $B_c^p$  constant is  $m_p^2 c^2 / e\hbar = 1.48 \cdot 10^{16}$  T and  $\kappa_p = 1.79$  is anomalous part of proton magnetic moment. In weak magnetic fields ( $B \ll B_c^p$ ) one gets  $E[B, s_z] \approx m_p + eB/2m_p - (2s_z)[1 + \kappa_p]\mu_N B$  for  $p_z \approx 0$ , which corresponds well also to Eq.(2) using  $\mu_p = (1 + \kappa_p)\mu_N$ .

Behavior of electrons in very strong magnetic fields was calculated by J. Schwinger, and for  $B > 10^{11}$  T the correction term  $\Delta E$  in Eq.(1) is [7]

$$\Delta E[B, s_z] = 2s_z m_e (\alpha/4\pi) [\ln(2B/B_c^e) - (C + 3/2)]^2 + \dots \quad (5)$$

where  $\alpha \simeq 1/137$ ,  $B_c^e = m_e^2 c^2 / e\hbar = 4.414 \cdot 10^9$  T, and  $C = 0.577$  is Euler's constant. For fields  $B < B_c^e$ , the correction for anomalous magnetic moment is  $\Delta E = 2s_z(\alpha/4\pi)m_e B/B_c^e$ , which corresponds to  $\Delta E \approx 2s_z 10^{-3} |\mu_e| B$ . For muon one can replace  $m_e \rightarrow m_\mu$  in the equations, which gives  $B_c^\mu = B_c^e (207)^2 = 1.89 \cdot 10^{14}$  T, and for  $B \ll B_c^\mu$  we have  $\Delta E \approx 2s_z 10^{-3} |\mu_\mu| B$ .



**Figure 2.** Energy of  $\rho^0$  and  $\rho^+$  ( $s_z = +1$ ) mesons [1] and  $\pi^+\pi^{-(0)}$  pairs in magnetic field.

### 3. Strong decays of $\rho(770)$ mesons in the magnetic field

Let us summarize the mechanism [1] which allows the lifetime of  $\rho(770)$  mesons to be prolonged due to the suppression of  $\rho \rightarrow \pi\pi$  strong decays. Energy of charged pseudoscalar ( $s = 0$ ) mesons increases in magnetic field according to Eq.(1) and therefore at some critical field value  $B^{cr}$  the mass of decay products may become equal to the mass of decaying neutral hadron. For  $\rho^0(770)$  meson this occurs in field  $B^{cr} \approx 2.2 \cdot 10^{15}$  T, as shown in Figure 2. Decay  $\rho^0 \rightarrow \pi^+\pi^-$  becomes therefore energetically forbidden in fields  $B > B^{cr}$ .

Magnetic moment  $\mu_{\rho^0}$  of  $\rho^0$  meson  $(u\bar{u} - d\bar{d})/\sqrt{2}$  state is usually [1] considered to be zero, neglecting in this way quadratic Zeeman interaction [5] of  $\rho^0(s_z=0)$  substate (see the behavior of ortho-Positronium ( $e^+e^-$ )  $J=1$  state in magnetic field [8]). However, charged  $\rho^+ = (u\bar{d})$  and  $\rho^- = (d\bar{u})$  mesons should have anomalous magnetic moments, which can be estimated also from the simple constituent quark model. For  $u, \bar{d}$  quarks with parallel spins in  $\rho^+(J=1)$  meson ground state, one has  $\mu_{\rho^+} = (\mu_u + \mu_{\bar{d}}) = 1.85\mu_N + 0.97\mu_N = \pm 2.82\mu_N$ .

In Figure 2 we show energy decrease of  $s_z = +1$  spin projection of charged  $\rho^\pm$  mesons evaluated according to publication [1], where condensation of  $\rho^\pm$  mesons is suggested to occur in static magnetic field. For majority of our estimates, however, it will be sufficient to consider weak-field approximations of the exact energy dispersion relations presented in Section 2.

#### 4. Enhanced $\gamma$ and $l^+l^-$ production from $\rho^0$ meson decays

In the case of  $\rho^0 \rightarrow \pi^+\pi^-$  decay suppression, the only potentially feasible strong decay channel  $\rho^0 \rightarrow \pi^0\pi^0$  is forbidden by  $C$  parity and isospin conservation. Therefore, closing of  $\pi^+\pi^-$  decay channel ( $BR = 99\%$  in vacuum) has intriguing consequences: other decay channels of type  $\rho^0 \rightarrow \pi^0\gamma$  ( $BR = 6 \cdot 10^{-4}$ ) and  $\rho^0 \rightarrow \eta\gamma$  ( $BR = 3 \cdot 10^{-4}$ ) may become strongly enhanced as shown in Table 1. This means decays of  $\rho^0$  meson in sufficiently strong magnetic field will produce excessive photons (from channels containing  $\pi^0, \eta$ ) and possibly also dilepton pairs.

**Table 1.**  $\rho^0$  decay branching ratios (BR) in B field.

channel	BR in $B \approx 0$	BR in $B > 2 \cdot 10^{15}$ T
$\pi^+\pi^-$	99%	0
$\pi^+\pi^-\gamma$	0.9%	0
$\pi^0\pi^0$	0	0*
$\pi^0\gamma$	$6 \cdot 10^{-4}$	64%
$\eta\gamma$	$3 \cdot 10^{-4}$	31%
$l^+l^-$	$0.9 \cdot 10^{-4}$	$\lesssim 1\%$
$\pi^0\pi^0\gamma$	$0.4 \cdot 10^{-4}$	4%
$\pi^+\pi^-\pi^0$	$1 \cdot 10^{-4}$	0
$\pi^+\pi^-\pi^+\pi^-$	$0.2 \cdot 10^{-4}$	0

\* Assuming  $\rho^0 \rightarrow \pi^0\pi^0$  remains closed in the magnetic field.

Regarding dilepton pair production via  $\rho^0 \rightarrow l^+l^-$  decays in the strong magnetic field, one can make the following simplified consideration:  $J=1$  angular momentum of decaying  $\rho^0$  meson must be conserved during decay process and this is achieved by parallel spin orientation (e.g.  $\uparrow\uparrow$  or  $\downarrow\downarrow$  for  $J_z = \pm 1$ ) of produced leptons  $l^+l^-$ . From Eq.(1) it is then clear that energy  $E[B, s_z]$  of one of the leptons will be increasing with the magnetic field, while energy of the other lepton remains almost constant (corrections  $\Delta E$  from Eq.(5) are negligible). At field  $B = 2.5 \cdot 10^{15}$  T the Equation (1) gives  $E[B, s_z = +1/2] \approx 550$  MeV for electrons or muons, which allows  $\rho^0 \rightarrow l^+l^-$  decays to happen with restricted phase-space (energy of  $l^+l^-$  pair does not exceed  $\rho^0$  mass).

Directions of the momenta of produced charged leptons leaving the region of overcritical field  $B^{cr}$  will be affected by the Lorentz force  $F = q \cdot \vec{v} \times \vec{B}$ , which distorts (influences) the reconstructed invariant mass of dilepton pairs. Therefore  $dN/dM_{l^+l^-}$  distribution of dileptons from the considered  $\rho^0$  meson decays (in volume containing strong magnetic field  $B \approx B^{cr}$ ) should/can be different from the expected  $dN/dM_{l^+l^-}$  spectrum in ( $B=0$ ) vacuum case.

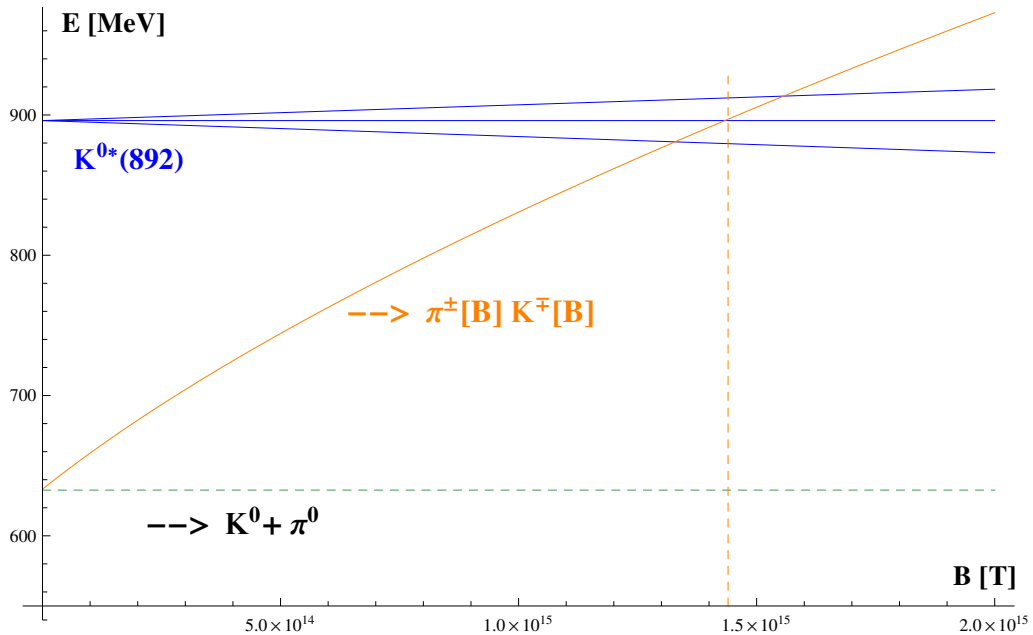
It is interesting to point out, that excessive elliptic flow asymmetry  $v_2$  of photons has been observed by PHENIX collaboration [9] in Au+Au collisions. A simulation with enhanced decay

probability of  $\rho^0 \rightarrow \gamma + \pi^0$  and  $\rho^0 \rightarrow \gamma + \eta$  channels could easily clarify, whether enlarged  $v_2$  of photons observed [9] may be explained by suppressed (for whatever reason)  $\rho^0 \rightarrow \pi^+\pi^-$  decays.

Assuming, that e.g. only 3% of  $\rho^0$  mesons produced in heavy ion collision have  $\pi^+\pi^-$  decay channel closed, branching ratios from the right side of Table 1 can easily generate the excess of photons or dileptons many times above the expected yield, without noticeably lowering the amount of  $\rho^0 \rightarrow \pi^+\pi^-$  decays from the remaining (97% unaffected)  $\rho^0$  mesons.

### 5. The case of $K^{0*}$ and $K^{\pm*}$ meson decays

Mesons  $K^{0*}(d\bar{s})$  and  $\bar{K}^{0*}(\bar{d}s)$  are ( $J = 1$ ) particles of mass  $M = 896$  MeV, which decay via strong decay channels  $\bar{K}^{0*}(K^{0*}) \rightarrow K^\pm + \pi^\mp$  and  $K^{0*} \rightarrow K^0 + \pi^0$  with probabilities 66% and 33% (ratio 2:1 is determined by Clebsch-Gordan coefficients originating from the isospin conservation). In Figure 3 we show the energy of  $(K^0\pi^0)$  and  $(K^\pm\pi^\mp)$  decay products and of decaying  $K^{0*}$  meson in the magnetic field. Triplet splitting observed for  $K^{0*}$  state comes from the magnetic moment of  $K^{0*}$  meson, which can be estimated to be  $\mu_{K^{0*}} = (\mu_d + \mu_{\bar{s}}) = -0.36\mu_N$  assuming parallel spin orientation for  $d, \bar{s}$  quarks in  $1S$  quantum state. Interaction energy of  $(K^{0*})$  particle with magnetic field is evaluated using expression  $E[B, J_z] = m_{K^{0*}} - B J_z \mu_{K^{0*}}$  which agrees with Eq.(3) in small field limit, when  $(2s_z) \rightarrow J_z$  substitution is used and  $p = 0$ .



**Figure 3.** Energy of  $K^{0*}(896)$  substates ( $m_z = \pm 1, 0$ ) and of  $K + \pi$  decay products in  $B$  field.

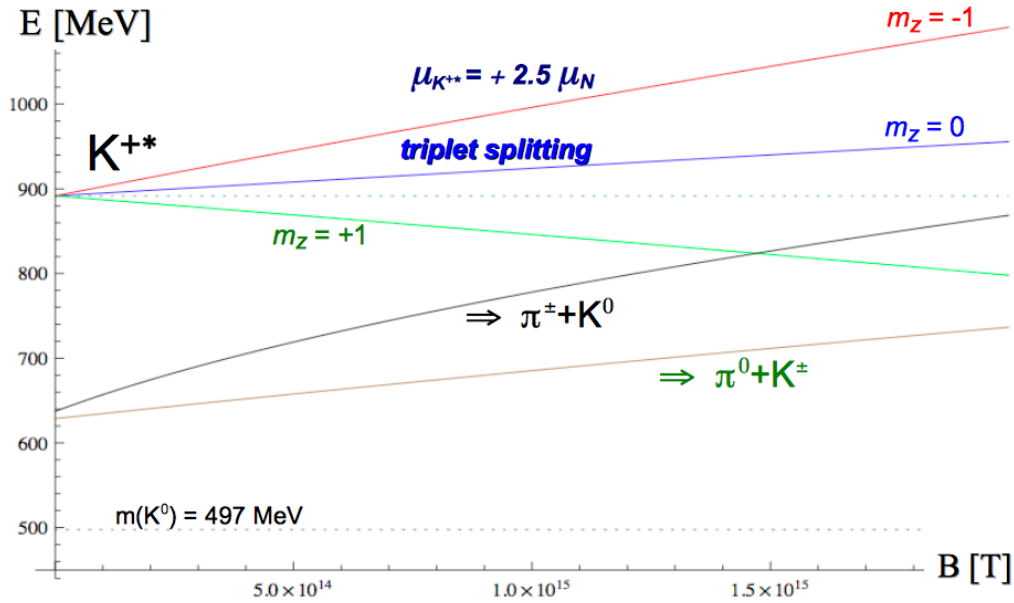
It is obvious that  $K^{0*} \rightarrow K^- + \pi^+$  decay is kinematically forbidden in field  $B > 1.5 \cdot 10^{15}$  T since the energy of  $(K^-, \pi^+)$  decay products exceeds the mass of  $K^{0*}$  meson. In such case the isospin conservation rule (leading to 2:1 ratio of decay probabilities) becomes violated, exactly as it happens with  $D^{0*} \rightarrow D\pi$  strong decays in vacuum ( $B = 0$ ).

Let us have a look what happens in the case of charged  $K^*$  meson decays. Magnetic moment of  $K^{\pm*}$  mesons  $\mu_{K^{\pm*}} = \pm(\mu_u + \mu_{\bar{s}}) = \pm(1.85 + 0.61) = \pm 2.46\mu_N$  is 7x larger compared to  $\mu_{K^{0*}}$  case and the additional contribution from  $n = 0$  Landau level modifies the energy of  $K^{\pm*}$  mesons. In the "small" field limit and static ( $p_z = 0$ ) case one can write

$$E[B, J_z] = m_{K^*} + |q_{K^*}|B/2m_{K^*} - J_z\mu_{K^*}B \quad (6)$$

which is sufficient for our purposes here. From Figure 4 one can conclude that both decay channels ( $K^{+*} \rightarrow K^+ + \pi^0$  and  $K^{+*} \rightarrow K^0 + \pi^+$ ) are affected and that the isospin violation effects are going to be much weaker if compared to the case of  $K^{0*}$  decays.

If  $K^{0*}$  and  $K^{\pm*}$  resonance yields in ultra-relativistic heavy ion collisions are determined from their  $K^{\pm} + \pi^{\mp}$  and  $K_s^0 + \pi^{\pm}$  decays, and strong magnetic field effects we discuss here are really significant, one can expect that  $K^{0*}$ ,  $K^{\pm*}$  yields (determined with the assumption of isospin conservation in strong decays) will be different. This happens because of different degree of the isospin violation we predict here for  $K^{0*}$  and  $K^{\pm*}$  mesons in the external magnetic field.



**Figure 4.** Energy of  $K^{+*}(892)$  substates  $(\pm 1, 0)$  and of  $K + \pi$  decay products in  $B$  field.

Additionally, from Figure 4 one can conclude that different  $J_z$  spin projections of  $K^{\pm*}(892)$  mesons are affected differently by the restricted phase-space available for  $K_s^0 + \pi^{\pm}$  decays, which may consequently lead to the measurable tensor polarization of  $K^{\pm*}$  mesons.

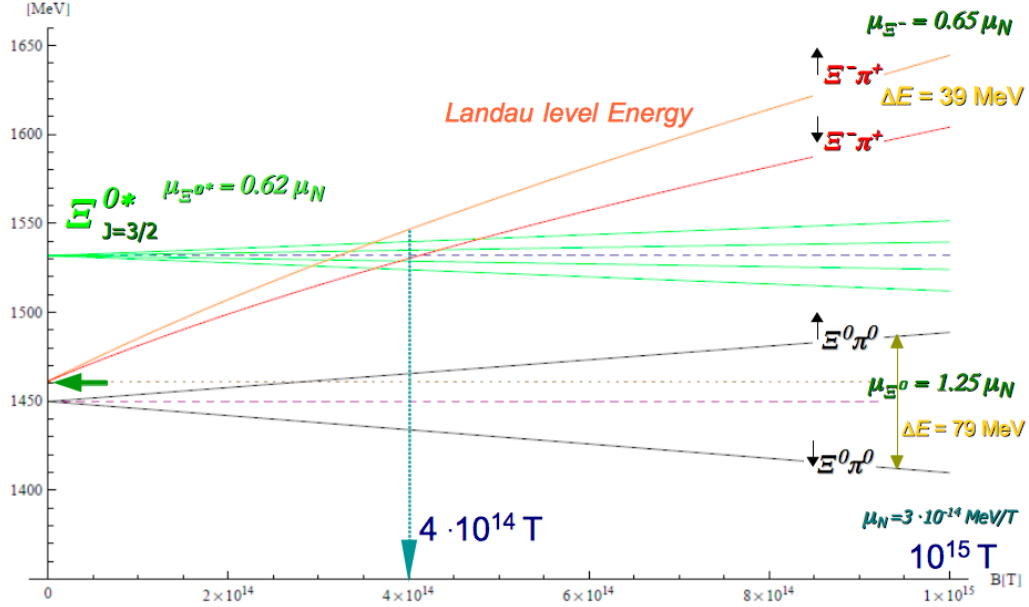
## 6. Decay of $\Lambda^*$ and $\Xi^{0*}$ in strong magnetic field

Energy of neutral baryons in the magnetic field is described by Eq.(3) which leads to quadruplet energy splitting for  $J = 3/2$  case. Magnetic moment of  $\Xi^{0*}(1530)$  resonance can be estimated as  $\mu_{\Xi^{0*}} = 2\mu_s + \mu_u = 0.62\mu_N$  using the constituent quark model for  $u^\uparrow s^\uparrow s^\uparrow$  quarks with parallel spins in  $L = 0$  quantum state, while for  $\Lambda^*(1520)$  we shall use value  $\mu_{\Lambda^*} = -0.2\mu_N$  [10].

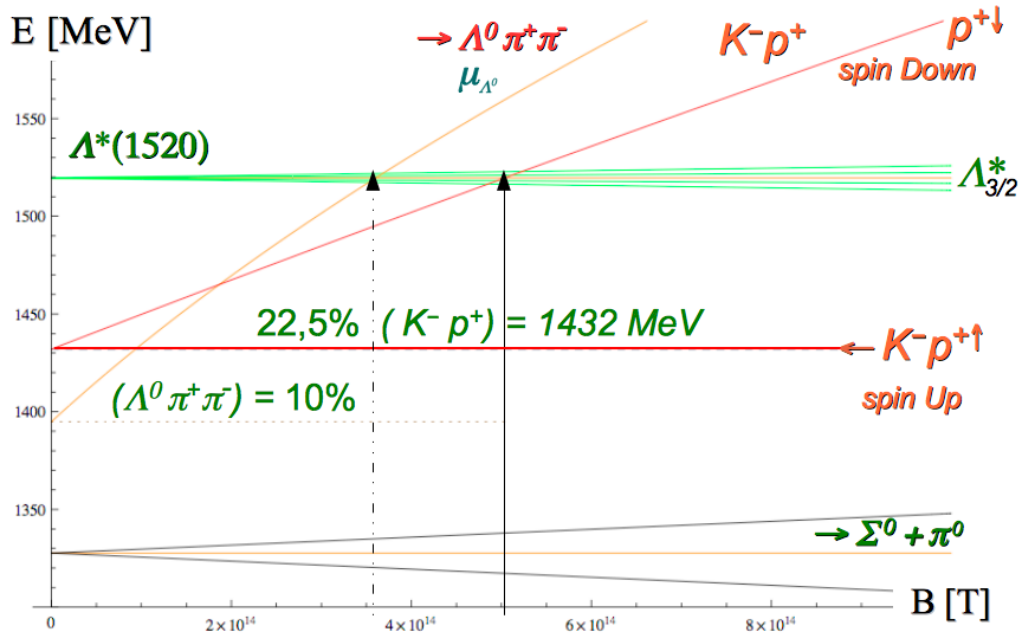
Figure 5 suggests that  $\Xi^{0*} \rightarrow \Xi^- + \pi^+$  decay channel becomes energetically forbidden in field  $B > 4 \cdot 10^{14}$  T for both orientations of  $\Xi^-$  spin  $s_z = \pm 1/2$ , while strong decays  $\Xi^{0*} \rightarrow \Xi^0 + \pi^0$  remain kinematically allowed. At even higher field strengths the interaction of magnetic moment  $\mu_{\Xi^0} = 1.25\mu_N$  with the external field (for  $s_z = -1/2$ ) may bring the energy of  $\Xi^0 + \pi^0$  pair above the mass of  $\Xi^{0*}$  substates, but this is not our concern here. Our main conclusion is, that due to the restricted phase space for  $\Xi^{0*} \rightarrow \Xi^- + \pi^+$  decays the isospin conservation in decays  $\Xi^{0*} \rightarrow \Xi + \pi$  can become violated in a sufficiently strong (static) magnetic fields.

Lifetime of  $\Xi^{0*}$  baryon state ( $\approx 21$  fm/c) is considerably longer compared to the expected magnetic field duration in relativistic heavy ion collisions, and therefore we are reluctant to relate the smaller yield of  $\Xi^{0*}$  baryons discussed at RHIC [11] with the magnetic field-induced

phenomena we study here. However, lifetime  $\tau_{\Lambda^*} \approx 13 \text{ fm}/c$  of resonance  $\Lambda^*(1520)$  is shorter, and therefore the behavior of  $\Lambda^*$  in the magnetic field may be of some relevance.



**Figure 5.** Energy of  $\Xi^{0*}(1532)$  baryon and of its decay products  $\Xi^-\pi^+$  and  $\Xi^0\pi^0$  in static magnetic field (using  $\mu_{\Xi^{0*}} = 2\mu_s + \mu_u = 0.62\mu_N$  and  $s_z = \pm 1/2$  orientations for  $\Xi^-$  and  $\Xi^0$ ).



**Figure 6.** Energy of  $\Lambda_{3/2}^*(1520)$  baryon ( $s_z = \pm 1/2, \pm 3/2$ ) substates (using  $\mu_{\Lambda^*} = -0.2\mu_N$ ) and of its decay products  $K^-p^+$ ,  $\Lambda^0\pi^+\pi^-$  and  $\Sigma^0\pi^0$  in the external static magnetic field.

In Figure 6 we show that decay channel  $\Lambda^* \rightarrow \Lambda^0\pi^+\pi^-$  becomes kinematically closed in field  $B > 3.5 \cdot 10^{14} \text{ T}$ , while channel  $\Lambda^* \rightarrow \Sigma^0\pi^0$  remains open in even much higher magnetic fields.

For decay  $\Lambda^* \rightarrow \Lambda^0 \pi^+ \pi^-$  we do not show  $\Lambda^0$  energy splitting due to  $\mu_{\Lambda^0} = -0.613\mu_N$  interaction with  $B$  field, because the effect is small, and this channel is not relevant here. However, for  $\Lambda^* \rightarrow p + K^-$  decay channel, which is used to reconstruct  $\Lambda^*(1520)$  in the experiments, the interaction  $\Delta E = -\vec{B} \cdot \vec{\mu}_p$  is important.

For  $s_z = -1/2$  proton spin projection, the energy of  $(p + K^-)$  pair rises above  $\Lambda^*$  mass at  $B > 5 \cdot 10^{14}$  T. This happens because  $n = 0$  Landau energy increase of  $K^-$  meson and Proton is supplemented by  $\Delta E = +\mu_p B$  positive energy contribution. However, in  $p^\uparrow (s_z = +1/2)$  case, the interaction of  $\mu_p = 2.79\mu_N$  with the field just compensates the rising contribution from  $n = 0$  Landau energy of charged  $K$  and  $p$  particles, what gives almost horizontal line at  $E = 1432$  MeV in Figure 6. Thus 50% of  $\Lambda^* \rightarrow p + K^-$  decays become suppressed in  $B > 5 \cdot 10^{14}$  T field, while  $\Lambda^* \rightarrow n + \bar{K}^0$  channel remains open and (almost) unaffected.

Precise measurement of  $\Lambda^*(1520)$  production in heavy ion collisions might be interesting, because  $\Lambda^*$  signal observed in peripheral and central Au+Au collisions at RHIC [12] is missing in non-central Au+Au collisions [13]. It remains to be resolved whether rescattering mechanism or just statistics, or decay channel suppression phenomena discussed here are responsible for the unobserved  $\Lambda^*(1520)$  peak in non-central Au+Au collisions at RHIC.

Decays of  $\Delta(1232)$  resonance with its short lifetime  $\tau \approx 2$  fm/c may also be influenced by magnetic fields of strength  $B \approx 5 \cdot 10^{14}$  T. Interested readers may find related information in [14].

## 7. Enhanced CP violation in $\eta_c$ and $\eta(547)$ decays due to magnetic field

In the preceding sections we have studied the interaction of magnetic field with charge and magnetic moments of hadrons. We have found that isospin conservation rules in strong decays of resonances may become violated due to kinematical (energy conservation) and phase-space reasons. However, the interaction of constituent quark magnetic moments with external magnetic field may change also the internal structure of hadrons and their decay properties, as we shall describe here.

It has been mentioned already by Gell-Mann and Pais [16] that rigorous conservation of C parity should be expected only in the absence of external fields. Indeed, ortho-Positronium (o-Ps)  $s_z = 0$  substate (which may decay only via o-Ps  $\rightarrow 3\gamma, 5\gamma$  channels in vacuum) obtains quantum admixture of para-Ps ( $J = 0$ ) state in the magnetic field. In such situation,  $(e^+ e^-)$  bound state with  $J = 1, s_z = 0$  quantum numbers can decay into  $\rightarrow \gamma\gamma$  pairs, which leads to experimentally observed [15] "magnetic field quenching" of ortho-Ps  $\rightarrow 3\gamma$  decays. The phenomenon occurs because new eigenstates  $\Psi_o^+$  and  $\Psi_p^-$  of the Hamiltonian containing the interaction of  $\mu_{e^+}$  and  $\mu_{e^-}$  magnetic moments with external magnetic field are (for  $B \neq 0$ ) superpositions of the original C parity eigenstates:  $\Psi_p(J = 0) = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2}$  and  $\Psi_o(J = 1, s_z = 0) = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2}$ :

$$\Psi_o^+ = \cos(\alpha)\Psi_o + \sin(\alpha)\Psi_p \quad \Psi_p^- = \cos(\alpha)\Psi_p - \sin(\alpha)\Psi_o \quad (7)$$

Mixing angle  $\alpha$  depends on the external magnetic field  $B$  as  $\sin(\alpha) = y/\sqrt{1+y^2}$ , where  $y = x/(1 + \sqrt{1+x^2})$  and  $x = 4\mu_e B/\Delta E_{hf}$  (here  $\Delta E_{hf} = 8.4 \cdot 10^{-4}$  eV is hyperfine energy splitting of Positronium [8]). Since constituent quarks have their magnetic moments (one may expect  $\mu_c \approx 0.4\mu_N$  and  $\mu_b \approx -0.07\mu_N$ ), eigenstates  $\Psi(nS)$  and  $\Upsilon(nS)$  of  $J = 1$  Quarkonium mesons should be affected [5] by external magnetic fields in a similar way as ortho-Positronium. Hyperfine energy splitting between  $(J = 0)$   $\eta_{c,b}$  mesons and  $(J = 1)$   $\Psi, \Upsilon$  states is 116 MeV and 71 MeV, and the required magnetic field for the mixing effect to occur in Quarkonium is [5]:  $B \approx 10^{14} - 10^{15}$  T. This phenomenon (suggested at 2012 DSPIN conference [17]) allows mesons, in quantum superposition state given by Eq.(7), to decay via new channels (in magnetic field). For example,  $s_z = 0$  substate of  $\Upsilon(1s)$  meson (decaying to  $\rightarrow ggg$  channel in 82% of cases) may disintegrate via much faster  $\rightarrow 2g$  (gluons) channel in the magnetic field, which can shorten the lifetime of  $\Upsilon$  mesons considerably [5] and also suppress the amount of  $\Upsilon \rightarrow l^+ l^-$  decays.



However, in this contribution we would like to discuss another consequence of the above mentioned quantum mixing phenomenon: In the magnetic field, para-Positronium  $J = 0$  state acquires admixture of o-Ps( $J = 1, s_z = 0$ ) substate. This is not very interesting in Positronium case, because lifetime ratio  $\tau_{o-Ps}/\tau_{p-Ps} \approx 10^3$  results in very small influence [8] of the magnetic field on para-Ps decays (possibility to decay via  $\rightarrow 3\gamma$  channel does not influence significantly quantum state which can decay via  $\rightarrow 2\gamma$  "fast" channel by default).

However, in the case of  $\eta(547)$  and  $\omega(782)$  mesons, the ratio of lifetimes is opposite  $\tau_\omega/\tau_\eta = 1.5 \cdot 10^{-4}$ , which means that  $r = 10^{-6}$  admixture of  $\omega$  meson in  $\Psi_p^- = \tilde{\eta}(547)$  superposition ( $J = 0$ ) state introduces  $\approx 0.6\%$  contamination from  $\omega$  decays [19]. This allows  $\tilde{\eta}(547)$  meson in the magnetic field to decay also into  $\rightarrow \pi^+\pi^-$  final states, which is otherwise forbidden by CP conservation at the level  $\text{BR}(\eta \rightarrow \pi^+\pi^- \leq 10^{-27})$  within Standard Model. For  $\eta_c - J/\Psi$  mixing, the enhancement of  $\eta_c \rightarrow \pi^+\pi^-$  decays is much less significant ( $\tau_\Psi/\tau_{\eta_c} \gg 1$ ).

It seems that magnetic field is able to enhance CP - violating decays of bound hadronic systems via quantum mixing - superposition phenomenon. This may occur only if "G" parity violation is significant ( $J/\Psi, \omega(782) \rightarrow \pi^+\pi^-$  decays cannot occur when G parity is conserved).

## 8. Superposition of $J/\Psi, \Upsilon$ with $\chi_{c,b}$ states in the external field

When Quarkonium vector ( $J=1$ ) mesons move in the magnetic field, they experience (in their rest frame) electric field  $E_t = -\gamma v_t B_z$ , which can influence their internal quantum state in a specific way. For Positronium, such phenomenon (motional Stark effect) has been studied carefully [4]. It has been established that  $s_z = \pm 1$  states of ortho-Positronium acquire admixture from  $1P$  ( $e^+e^-$ ) states (these correspond to  $\chi_c(J=0, 1, 2)$  mesons in the case of Charmonium). For example, eigenstate  $\tilde{\Psi}^{s_z}(c\bar{c})$  with  $J=1, L=0, s_z=+1$  quantum numbers of the Hamiltonian containing the interaction term for external electric fields is

$$\tilde{\Psi}^{+1}(2s) = \Psi^{+1}(2s) - x_2 \left( \frac{\chi_{c2}^0}{\sqrt{6}} - \chi_{c2}^{+2} \right) - x_1 \frac{\chi_{c1}^0}{\sqrt{2}} + x_0 \frac{\chi_{c0}^0}{\sqrt{3}} \quad (8)$$

where parameters  $x_2, x_1, x_0$  depend on "hyperfine" energy splittings  $\Delta E_{hf}$  between  $\Psi(2s)$  and  $\chi_{c0}, \chi_{c1}, \chi_{c2}$  mesons. One has  $x_2 = 3\sqrt{2} q_c \langle r_0 \rangle E_t / \Delta E_{hf} (\Psi_{2s} - \chi_{c2}) = 2\sqrt{2} e \langle r_0 \rangle E_t / 130 \text{ MeV}$ , where  $\langle r_0 \rangle = 0.45 \text{ fm}$  is the "size" of  $\Psi(2s)$  state. Expressions for  $x_1$  and  $x_0$  are the same as  $x_2$ , just  $\Delta E_{hf}$  parameters are 175 MeV and 271 MeV for  $(\Psi_{2s} - \chi_{c1})$  and  $(\Psi_{2s} - \chi_{c0})$  mass differences.

We mention this here to point out, that  $\Psi(nS) - \chi_c(nP)$  and  $\Upsilon(nS) - \chi_b(\tilde{n}P)$  superpositions (in external electric field) are more significant in case of small  $\Delta E_{hf}$  mass splittings between  $\chi_{c,b}$  and triplet  $J=1$  Quarkonium states. From the known masses of Charmonium and Bottomium mesons one can find that  $\Psi(2s)$  and  $\Upsilon(2s, 3s)$  states are more affected by quantum mixing effects (in the magnetic and electric field) than  $J/\Psi(1s)$  and  $\Upsilon(1s)$  mesons.

Admixtures of  $\chi_{c,b}$  and  $\eta_{c,b}$  states in  $\Upsilon(ns)$  and  $\Psi(ns)$  mesons allow them to decay via "fast" ( $\rightarrow gg$ ) channels, lowering the yield of  $l^+l^-$  pairs from their decays. We suggest that suppression/disappearance of  $\Upsilon(2s, 3s)$  yields observed in Pb+Pb collisions at LHC [18] might possibly be related also to the quantum mixing behavior we have discussed here.

## 9. Summary

We have studied the influence of external magnetic and motional electric field on decay properties of mesons and baryonic resonances. We suggest that isospin conservation rules determining branching ratios for various strong decay channels of  $K^*, \Xi^*, \Lambda^*$  hadronic resonances may become violated in the magnetic field ( $B \approx 10^{14} \text{ T}$ ) due to the restricted phase-space and energy conservation. In the case of  $\rho^0 \rightarrow \pi^+\pi^-$  decay suppression, we speculate that enhanced photon and dilepton production may occur. CP violation in  $\eta \rightarrow \pi^+\pi^-$  decay channel has been predicted to be enlarged in the magnetic field, and the influence of motional electric field on  $\Psi(ns)$  and  $\Upsilon(ns)$  Quarkonium states has been considered.

## Acknowledgments

This work was performed within project No.2/0197/14 of the Slovak Grant Agency VEGA. Financial support from Slovak Research and Development Agency project No. APVV-0177-11 is acknowledged. The author thanks to Slovak CERN committee for the encouraging support and to K. Šafařík for the kind hospitality at CERN, where some of ideas presented here had been elaborated. The invitation to give a talk at WWND 2015 conference and excellent management of this scientific meeting (by R. Bellwied, F. Geurts, and A. Timmins) are highly appreciated.

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